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Sap velocity, transpiration and water use efficiency of drip-irrigated cotton in response to chemical topping and row spacing

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ABSTRACT

Directly measuring plant transpiration of field crops and determining water use efficiency are difficult but essential to understand plant-water relations. In this study, we aimed to quantify plant transpiration and water use efficiency at diurnal and daily bases using sap flow measurements in cotton growing under plastic film cover and drip irrigation in relation to row configurations and chemical topping. Field experiment was carried out in 2020–2021 in Xinjiang, China. The experiment included two topping treatments: chemical topping using heavy amount of mepiquat chloride and traditional manual topping; and two typical row spacing for machine-harvesting: equal row spacing (76 cm) and narrow-wide row spacing (10 cm + 66 cm). Sap flow was measured using a heat ratio method after cotton first flowering stage and then calculated to transpiration per plant and per unit ground area. Chemical topping increased cotton plant height by 12%, leaf area index by 13%, and stem diameter by 9% but did not affect cotton lint yield compared with manual topping across two years and row configurations. The sap velocity of drip-irrigated cotton ranged overall from 20 to 45 cm hr^{-1} at the daytime and close to zero at nighttime. Across two years, the daily transpiration in chemical topping after flowering was 5.57 mm d^{-1} and 14.8% higher than in manual topping. That in narrow-wide row spacing was higher than in equal rows. However, the water use efficiency did not differ between topping and row spacing treatments, being 5.64 kg m^{-3} on average for aboveground dry matter. This knowledge would be useful to optimize cotton irrigation managements and to improve crop models by knowing exact plant transpiration at both plant and system levels.

1. Introduction

Cotton (*Gossypium hirsutum* L.) is an important cash crop and raw material for the textile industry and have a significant impact on the world economy (Jans et al., 2021). Xinjiang grows around 83% cotton and produces 89% of total production of China in 2021 (http://www.stats.gov.cn), and also is an important cotton producing region in the world (Han et al., 2020). Cotton in Xinjiang faces the challenge of the limitations in water and temperature resources. Cotton in Xinjiang grows in high plant population density (14–32 plants m^{-2}), and drip irrigation is popular applied under plastic film cover (Tan et al., 2017). Because of machine-harvest (Wang et al., 2021), cotton requires an equal (76 cm) or a narrow-wide (10 + 66 cm) row spacing. Due to the shortage of labors, cotton topping as a key traditional practice (Aydin and Arslan, 2018) is changing from manual topping to chemical topping (Dai et al., 2022), using a heavy amount of mepiquat chloride (MC) to terminate buds growth.

Water use efficiency (WUE), defined as crop grain or biomass yield produced with unit of actual evapotranspiration (ET) or plant transpiration, represents how plants can efficiently convert water into carbohydrates (Yuan et al., 2013). The WUE varies between C3 and C4 crops, climate, irrigation systems and schedules, soil managements and canopy architecture (Zhao et al., 2012). Plastic film cover promotes cotton growth and development and reduces soil evaporation; thus improves crop yield and water use efficiency (Tan et al., 2017). Drip-irrigated cotton in narrow-wide row spacing with 87% of film cover potentially

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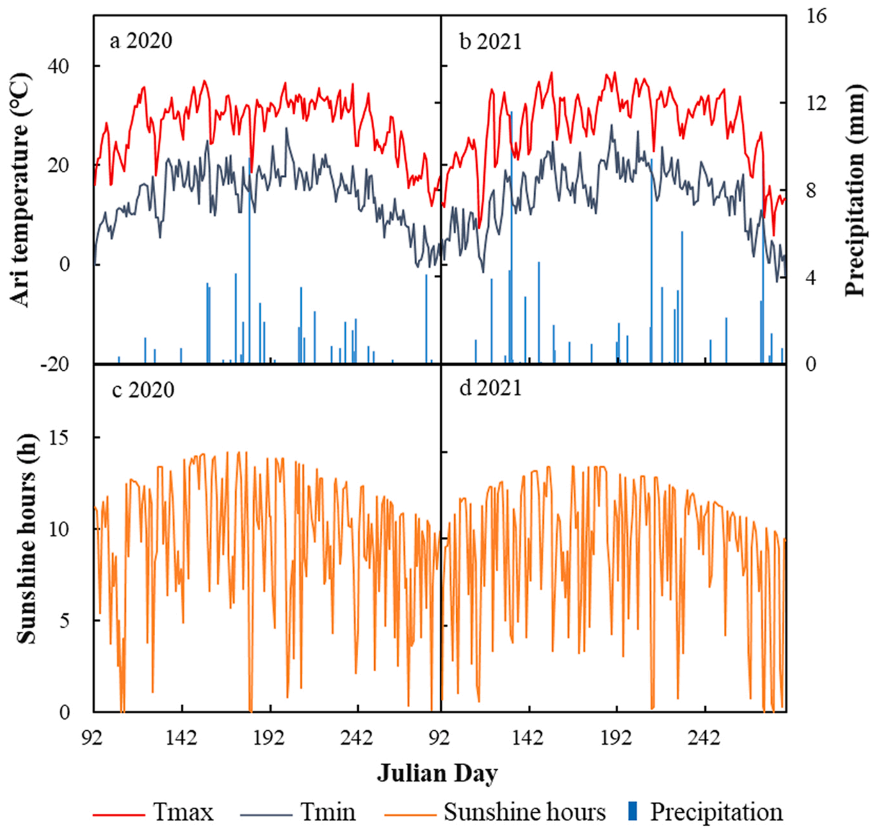

Fig. 1. Weather conditions during cotton growing season from April to October in Wulanwusu, Shihezi, China in 2020–2021.

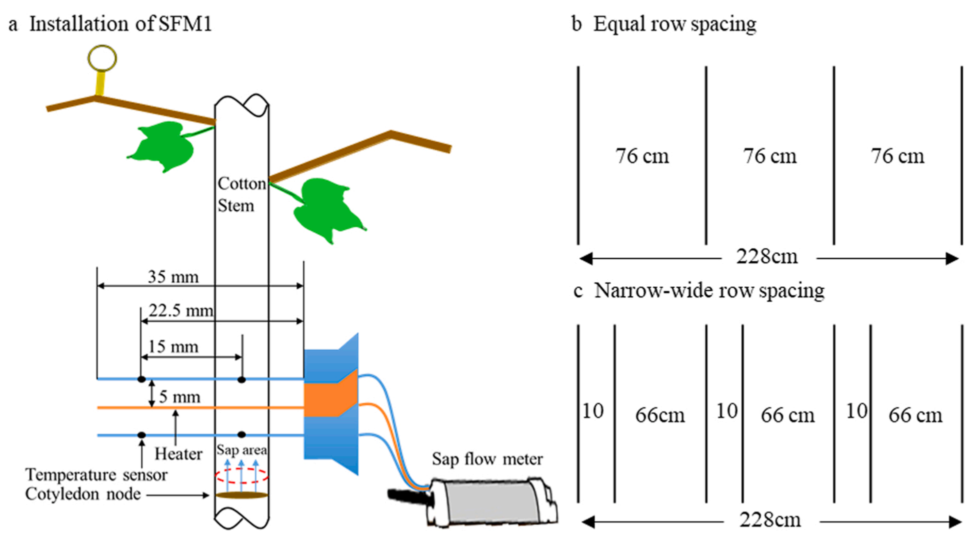

Fig. 2. Installation diagram of sap flow meter (SFM1) and layouts of row configurations in the experiment.

saves water and increases cotton yields (Wang et al., 2021). Plant growth regulators e.g. MC increases water use efficiency by decreasing stomatal conductance and transpiration rate (dos Santos et al., 2021; Kumar et al., 2001). However, there is little quantitative information available if plant transpiration and water use efficiency are affected by row spacing and chemical topping.

To quantify water use efficiency based on plant transpiration is rather difficult because it is highly affected by atmosphere, soil and agronomy managements (Merta et al., 2001). Determining plant transpiration at field conditions exists undesirable limitations (Alfieri et al., 2012; Zhang et al., 2014) in most of current methodologies, such as photosynthesis system (Zhang et al., 2014), sap flow measurement using thermal dissipation probe (TDP) (Reyes-Acosta and Lubczynski, 2014), eddy covariance (Baldocchi, 2003; Wilson et al., 2001), and lysimeter (Agam et al., 2012). The combination of soil water balance and Penman-Monteith model estimates crop transpiration based on climate, soil and crop factors and is widely applied in many situations (Petersen et al., 1992; Colaizzi et al., 2014). However, it has difficulties to precisely separate soil evaporation and plant transpiration. The heat ratio method (HRM) for sap flow measurement provides possibility to measure sap flow of cotton. The HRM sap flow meter is reliable for capturing small changes in sap flow during a day and provides important

Table 1
Yield and plant traits of cotton under different topping and row configuration treatments in Shihezi, Xinjiang in 2020–2021.

Year	Row configuration	Topping method	Plant height	Stem diameter internode	Leaf area index	Lint yield
			cm	mm	(m^2 m^{-2})	kg ha^{-1}
2020	Equal row spacing	Chemical topping	60.6a	7.95a	3.45a	1983a
		Manual topping	54.8a	7.82a	3.10a	1767a
		SE	2.73	0.09	0.17	176
	Narrow-wide row spacing	Chemical topping	72.8a	8.67a	5.03a	2300a
		Manual topping	64.9a	8.12a	4.82a	2150a
		SE	1.49	0.27	0.37	256
2021	Equal row spacing	Chemical topping	89.3a	10.1a	4.70a	2950a
		Manual topping	80.0a	8.91a	4.21a	2717a
		SE	4.03	0.36	0.31	160
	Narrow-wide row spacing	Chemical topping	87.3a	10.8a	5.38a	2800a
		Manual topping	76.7a	9.51a	4.29b	2317a
		SE	4.14	0.87	0.12	227
P	Topping		0.003	0.029	0.039	0.209
	Row spacing		0.093	0.095	0.000	0.804
	Year		0.000	0.000	0.004	0.003

Same small letters indicates no significant difference between topping treatments within same row configuration and year at a= 0.05.
Plant height, stem diameter and leaf area index were measured on 15 August in 2020 and 20 August in 2021.

physiological information in understanding the mechanism of plant-water relations (Alarcon et al., 2000). The HRM measures very low sap flows with less damage to the crops (Bleby et al., 2004) and allows to measure sap flow of field crops with thin stems such as cotton, soybean and maize, but this method is highly sensitive to errors caused by inaccuracies in probe spacing (Burgess et al., 2001). Another disadvantage of HRM sap flow meter is difficult to measure cotton transpiration during seedling period.

Chemical topping increases cotton net photosynthetic rate, stomatal conductivity and improves light distribution within the canopy (Liang et al., 2020). However, Tung et al. (2018) also found mepiquat chloride did not favor leaf photosynthesis and carbohydrate metabolism. We hypothesized that the cotton with chemical topping would increase water use efficiency by increasing net photosynthesis and growth rate because of plant morphological and physiological changes, and the practices that affecting canopy architecture such as narrow-wide row spacing might also play an important role on improving plant transpiration and WUE.

The objectives of this study were (a) to quantify crop growth and transpiration at diurnal, daily and seasonal bases for chemical topping under different row spacing when the crop was well irrigated; and (b) to test our hypothesis if WUE could be increased by chemical topping and narrow-wide row spacing.

2. Materials and methods

2.1. Study site

A two-year field experiment was conducted in 2020 and 2021 at the Wulanwusu Agrometeorological Experiment Station (44°17′N, 85°49′E) in Xinjiang Uygur Autonomous Region of China. The climate is temperate continental, and above 10 °C cumulative temperature is 3610 °Cd from 1980 to 2018. In experimental years (2020–2021), the annual

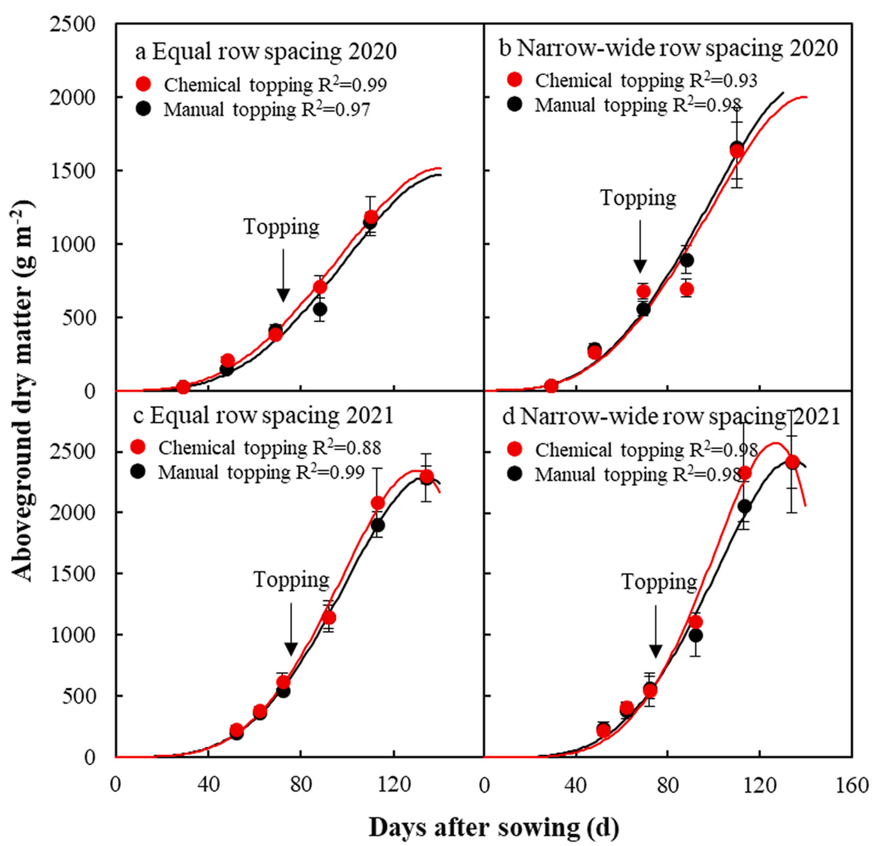

Fig. 3. Fitted (lines) and observed (points) aboveground dry matter in cotton under different topping methods and row configurations in 2020–2021.

Table 2
Fitted parameters of the beta growth function for cotton growth in different topping and row spacing treatments in 2020–2021.

Year	Row configuration	Topping method	W_m g m^{-2}	t_e d	t_m d	C_m g m^{-2} d^{-1}	nRMSE (%)
2020	Equal row spacing	Chemical topping	1610a	136a	98.1a	24.0a	11.6
		Manual topping	1281b	132a	95.8a	19.3a	15.5
		SE	43.2	3.04	1.50	1.10	
	Narrow-wide row spacing	Chemical topping	2074a	136a	98.3a	30.3a	23.7
		Manual topping	1740a	140a	92.7a	22.6a	23.6
		SE	113	1.53	3.10	2.24	
2021	Equal row spacing	Chemical topping	2349a	130a	98.4a	39.0a	20.4
		Manual topping	2141a	132a	98.7a	33.9a	1.85
		SE	116	1.63	0.75	2.57	
	Narrow-wide row spacing	Chemical topping	2583a	127a	100.3a	48.9a	11.6
		Manual topping	2455a	133a	102.3a	40.9a	11.2
		SE	132	2.49	0.98	5.08	
P	Topping		0.028	0.168	0.318	0.016	
	Row configuration		0.003	0.273	0.630	0.012	
	Year		0.000	0.002	0.018	0.000	

Same small letters indicate no significant difference between topping treatment within same row configurations at a= 0.05 level.
The W_m indicates the maximum value of dry matter, t_e is the time at which W_m is reached. The C_m indicates the daily maximum growth rate, and t_m is the time reaching it. The time is days after sowing.

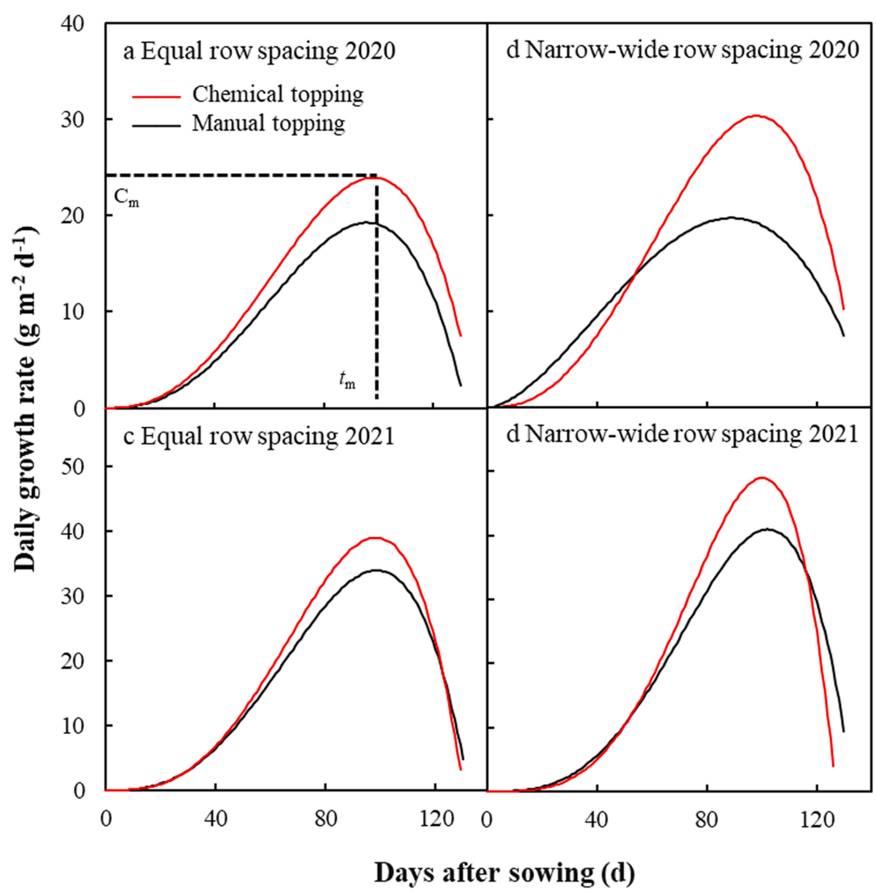

Fig. 4. Daily crop growth rate of cotton in different topping and row spacing treatments in 2020–2021.

mean air temperature during the cotton growing season (April to October) was 20.8 °C, annual sunshine hours were 1863 h, annual total precipitation was 150 mm (Fig. 1). The soil texture at the experimental field was sandy loam with a bulk density of 1.41 g cm^{-3}. The field capacity was 0.28 m^3 m^{-3}. The organic matter content within 0–40 cm soil layer was 17 g kg^{-1}, total N content of 0.91 g kg^{-1}, alkali soluble N of 84.0 mg kg^{-1}, available P of 91.5 mg kg^{-1} and available K of 315 mg kg^{-1}.

2.2. Experimental design

The field experiment was in a randomized complete block design with 3 replicates. The treatments included 2 row spacing, i.e. equal row spacing of 76 cm, and narrow-wide row spacing of 10 + 66 cm alternatively (Fig. 2). The plant distance in equal row spacing was 7.5 cm, resulting in a plant population density of 20 plants m^{-2}. In narrow-wide row spacing, the plant distance was 13.2 cm and population density was 26 plants m^{-2}. The slight difference in plant density was due to the

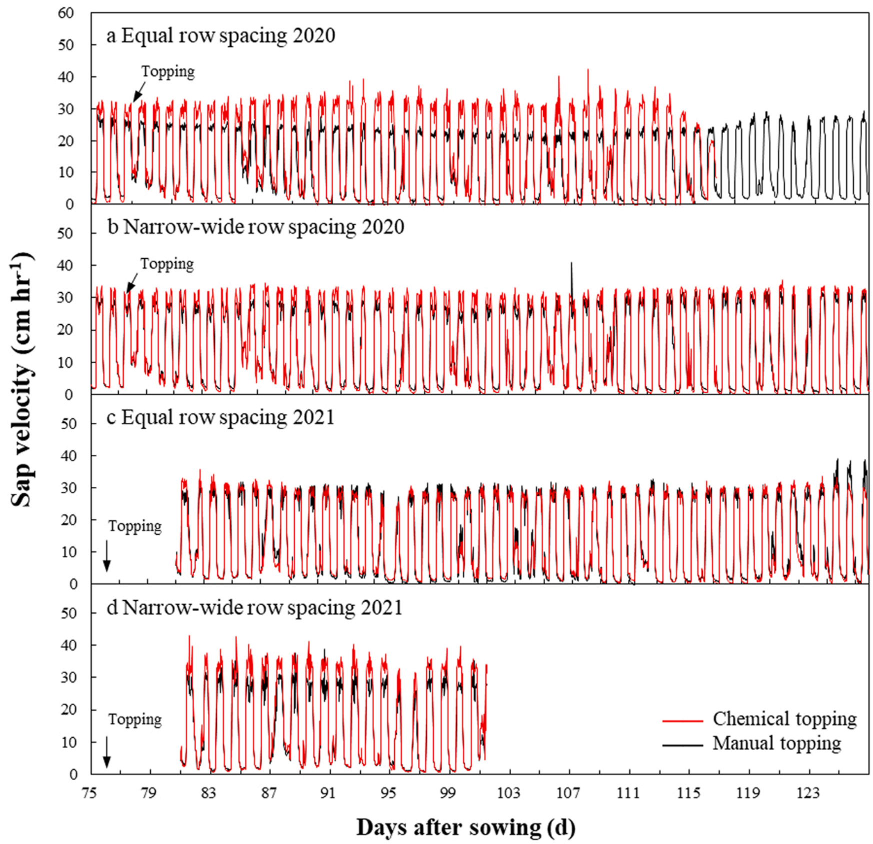

Fig. 5. Sap velocity during cotton flowering to boll open period (July to September) for topping and row spacing treatments in Shihezi, China in 2020 and 2021.

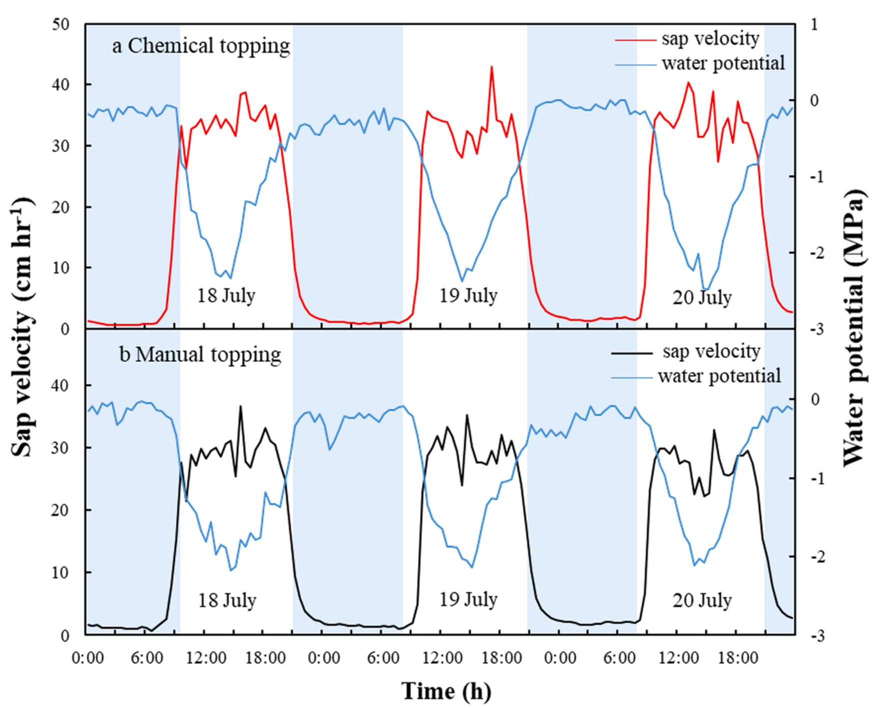

Fig. 6. Diurnal course of stem sap flow and water potential in three sunny days in equal row spacing with a plant density of 20 plants m^{-2} in 2021. The area with grey color indicates the time (night) from 18:00–8:00 of the next day.

machine design. The treatments also include two topping methods: manual topping and chemical topping. The chemical topping applied 225 g ha^{-1} of mepiquat chloride by a manual sprayer to terminate buds growth. The manual topping was cut out main stem buds (top 2–3 young leaves) by hand. Both topping treatments were performed on 10 July 2020 and 11 July 2021. Ten days after first applying chemical for

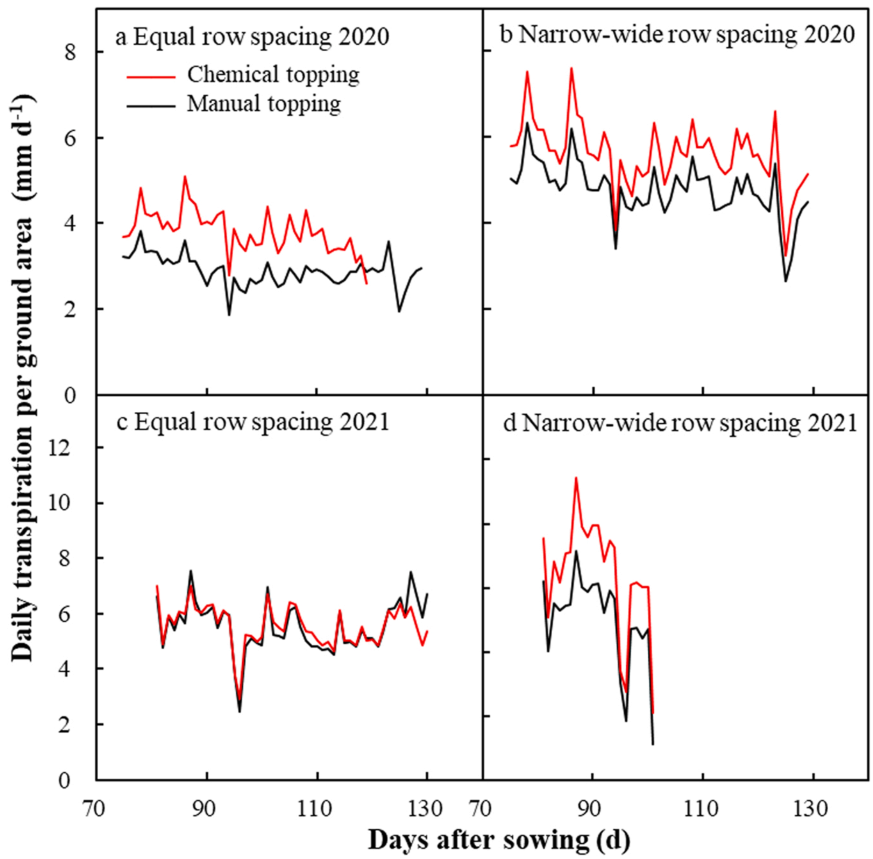

Fig. 7. Daily transpiration in cotton under different topping and row spacing treatments in 2020–2021.

topping, another 150 g ha^{-1} mepiquat chloride was used to restrict further buds growth.

Each plot was 7 m long and 4.5 m wide with a total area of 31.5 m^2. Cotton cultivar was Xinluzao 78 in both years. Cotton was sown on 24 April in 2020 and 26 April in 2021. Plastic film was covered by machine at the same time. The cotton was harvested on 10 October in 2020 and 20 October in 2021. The drip tubers were set under plastic film. The proportion of film cover for all treatments was 87% of soil surface. Total 480 mm of water was given during crop growing season in six times in 2020 and seven times in 2021. The irrigation interval was 10–15 days. The fertilizer was applied by drip irrigation system. Total input N was 680 kg ha^{-1}, P 270 kg ha^{-1} and K 80 kg ha^{-1} according to farmers' practice.

2.3. Measurements of crop growth and yield

To determine aboveground dry matter, plant sampling was conducted five times: 22 May, 10 June, 1 July, 20 July, 11 August in 2020 and six times in 2021: 15 June, 25 June, 5 July, 25 July, 15 August, 5 September. For each sampling, 3 plants were taken for each plot. The samples were separated into leaves, stems, and fruits at first and then were dried at 80 °C for 48 h until a constant weight was reached.

Plant height, stem diameter of the first internode and the size of leaf (length and width) were measured for each plot on 20 August in 2020 and 23 August in 2021, when these reached its maximum. Leaf area per plant was calculated by multiplying the length, width of the leaf and a shape factor 0.83 (Zhang et al., 2008a). Leaf area index (LAI) was leaf area per plant multiplying plant density. Cotton lint yield was measured in 4 m^2 sampling area for each plot at harvest times.

2.4. Sap flow and stem water potential measurements

Sap flow was measured by sap flow meter SFM1 (ICT International, Armidale, Australia) from 8 July (first flowering stage) to 30 August in 2020 (boll open stage), and 13 July to 30 August in 2021. The SFM1 uses heat ratio method (HRM) to determine sap velocity in a plant by measuring temperature ratios caused by upwards and downwards sap movements. The temperatures were measured by thermistors in measuring probes (Schoppach et al., 2021). The positions of probe installation and thermistors in a plant were shown in Fig. 2. One plant for each treatment was selected to install one SFM1. Only outer points of the thermistors in a plant stem were used to calculate transpiration and the 20–25 mm tail of the probe (inner points) was left outside of the stem and was wrapped by tin paper to prevent direct radiation for avoiding possible errors from instant heating. The SFM1 is not suitable for cotton seedling because of the installation requirement of minimum stem. During the installation of SFM1, handle driller was used to keep precisely level of drilling holes. To avoid heating damage of stem, the drill fillings were frequently removed to keep low temperature of the driller. To check if the plant suffers water stress, two stem water potential sensors PSY1 (ICT International, Armidale, Australia) were installed in main stem close to the SFM1 in a plant in 2021. Before installation of PSY1, the plant was trimmed off stem bark with a knife, water potential probe was fixed and sealed with silicone and probe was wrapped by tinfoil to prevent radiation. The data for both SFM1 and PSY1 were recorded at a time interval of 30 min.

The heat ratio method (HRM) measures the ratio of temperature increases of two thermistors between downstream and upstream at the points in same distance after release of a heat pulse. Heat pulse velocity is calculated as follows.

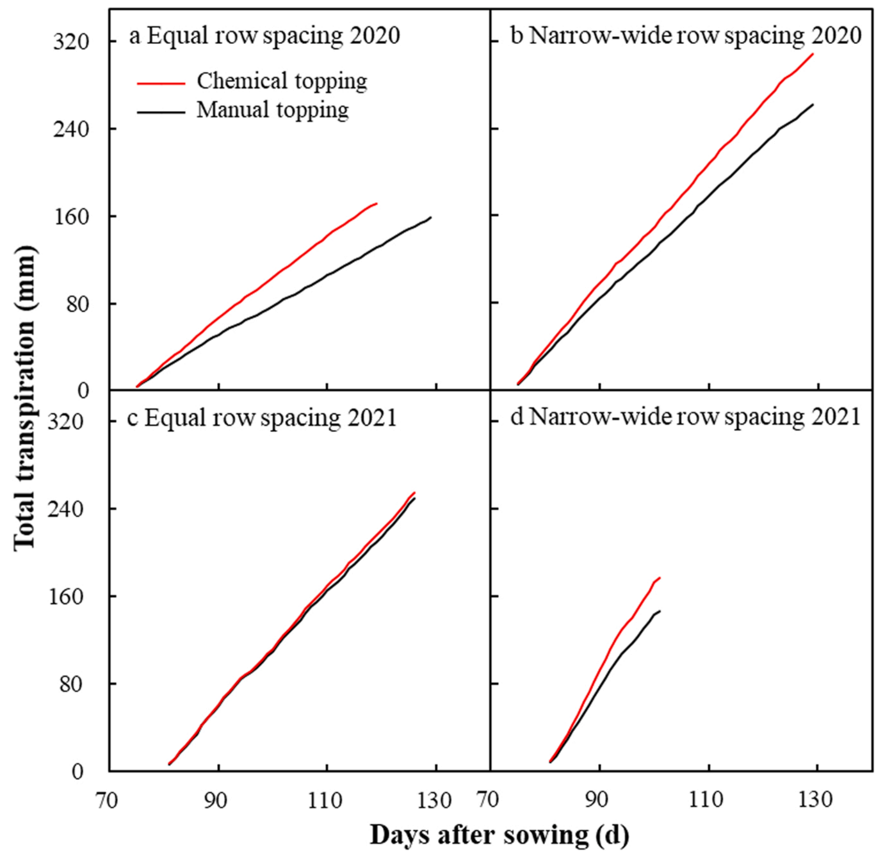

Fig. 8. Total transpiration during flowering and boll stage in cotton under different topping and row spacing treatments in 2020–2021.

$$V_h = \frac{k}{x}\ln\left(\frac{v_1}{v_2}\right)3600 \quad (1)$$

where k is thermal diffusivity of green wood, setting to 0.0025 $cm^2\ s^{-1}$ in the study (Marshall, 1958), x is the distance between the heater needles and either probe, fixed to 0.5 cm, and v_1 and v_2 are the increase of temperatures in paired thermistors (Burgess et al., 2001).

Cotton daily transpiration (DTr, mm d^{-1}) per unit ground area was calculated by plant transpiration (Tr) and the plant population density (PPD, plant m^{-2}) in Equ. 2. The Tr ($cm^3\ d^{-1}$ $plant^{-1}$) is the production of daily average sap velocity (V_h, cm hr^{-1}) within 24 h and sap area of a plant (SA, cm^2). Since heartwood formation generally begins after 32 months in most woody species (Santos et al., 2021), all cotton stem is considered as sapwood (Zhang et al., 2020). Thus, the SA is calculated using measured stem diameter (Equ. 4). Stem diameters (D, cm) was measured at the first internode, where the SFM1 was installed. After first flowering stage, the stem diameter at the bottom node stopped growth. The total transpiration during a period is the sum up of DTr, in this study, from the flowering to boll open.

$$DTr = Tr \times PPD \quad (2)$$

$$Tr = V_h \times SA \times 24 \quad (3)$$

$$SA = 3.14 \times (D/2)^2 \quad (4)$$

where V_h is the average sap velocity per hour that calculates from the measurements of 30 min interval. The sap flow meter was powered by a solar panel. Because of the problem of power supply, some data of narrow-wide row spacing were missing in 2021.

2.5. Data analysis

We used a beta function with three stable parameters to fit cotton growth (Mao et al., 2018). According to the equation, the daily growth rate (dw/dt) of aboveground dry matter was calculated directly by using the first derivative of the equation.

$$w = w_{max}\left(1 + \frac{t_e - t}{t_e - t_m}\right)\left(\frac{t}{t_e}\right)^{\frac{t_e}{t_e - t_m}} \quad (5)$$

$$\frac{dw}{dt} = c_m\left(\frac{t_e - t}{t_e - t_m}\right)\left(\frac{t}{t_m}\right)^{\frac{t_m}{t_e - t_m}} \quad (6)$$

$$c_m = w_{max}\frac{2t_e - t_m}{t_e(t_e - t_m)}\left(\frac{t_m}{t_e}\right)^{\frac{t_m}{t_e - t_m}} \quad (7)$$

where t_e (d) is the days after sowing (DAS) when reaching the maximum aboveground dry matter W_{max} (g m^{-2}). The t_m (d) is DAS when reaching maximum growth rate C_m (g m^{-2} d^{-1}).

To determine variation of water use efficiency (WUE, kg m^{-3}) during cotton growth season, we calculated the WUE at a daily base, as the ratio of daily growth rate (g m^{-2} d^{-1}) and DTr (mm d^{-1}).

$$WUE = \frac{dw/dt}{DTr} \quad (8)$$

where dw/dt is fitted daily growth rate for each treatment and DTr is measured by sap flow meter. The overall WUE during flowering to boll open stages was the slope in a linear regression between accumulative aboveground dry matter and total transpiration (accumulative DTr) during a period.

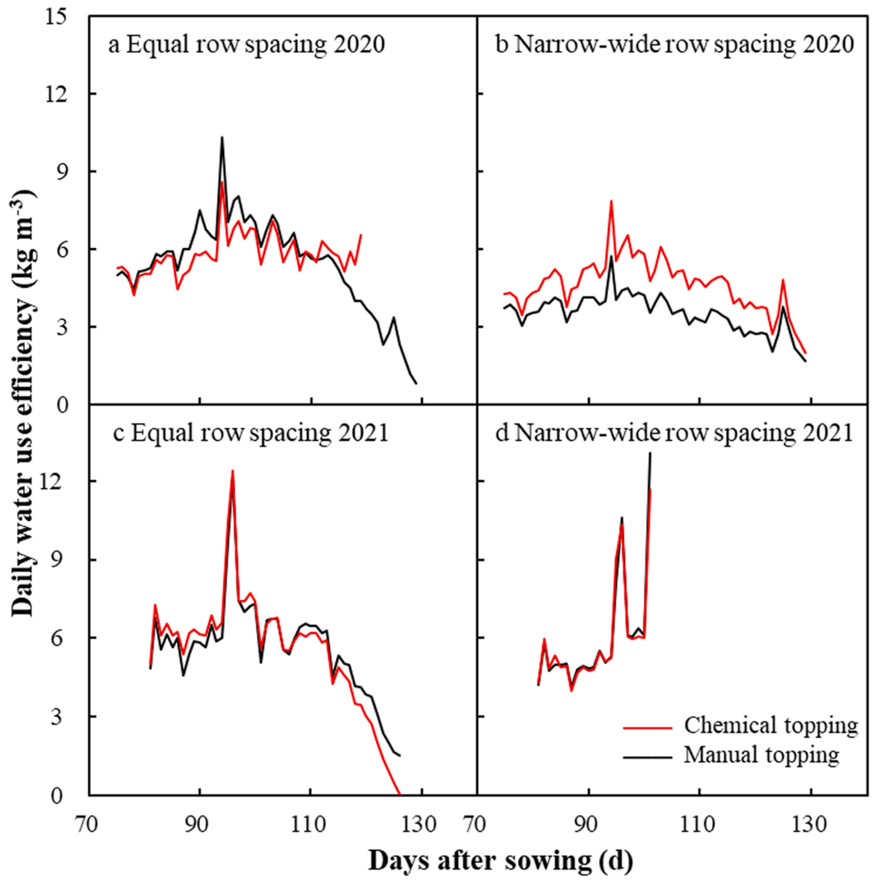

Fig. 9. Daily water use efficiency in drip-irrigated cotton under different topping and row spacing treatments in Shihezi China in 2020–2021.

2.6. Statistical analysis

The cotton growth was fitted by nonlinear regression in SPSS. The main and interactive effects of fitting parameters (W_{max}, t_m and t_e) were analyzed by using the general linear model program in SPSS, putting treatments and year as fixed factors and replicating as a random factor. Least significant differences (LSD) were used to separate treatment mean differences at 0.05 level.

3. Results

3.1. Yield and plant traits

Lint yield was not significantly ($P > 0.05$) affected by topping and row spacing treatments but significantly interacted with year. There was no interactions between topping treatment and row configuration ($P > 0.05$). However, lint yield was significantly ($P < 0.05$) affected by year, with an average yield of 2.7 ton ha^{-1} in 2021 and 2.1 ton ha^{-1} in 2020 (Table 1).

Chemical topping significantly increased plant height by 12% and stem diameter of the first internode by 9% comparing with manual topping (Table 1). Row configuration did not affect ($P > 0.05$) plant height and stem diameter. There was a significant difference in plant height and stem diameter between the two years (Table 1).

The maximal LAI was significantly affected by topping treatment and row configuration (Table 1). The LAI in chemical topping was 4.64 ± 0.84, 13% higher than in manual topping (4.11 ± 0.72), while that in narrow-wide row spacing was 4.88 ± 0.46 and was 26% higher in equal row spacing (3.87 ± 0.72). In 2021, LAI was higher than that in 2020, especially in equal row spacing.

3.2. Growth dynamics

Cotton growth course captured well with the beta function (Fig. 3), with an R^2 above 0.88 for all treatments and years. Maximum above-ground dry matter (W_m) was, across two years and two row spacing, 13.1% greater ($P < 0.05$) in chemical topping than in manual topping. The W_m was 19.9% higher ($P < 0.01$) in narrow-wide row spacing than in equal row spacing (Table 2). The W_m varied significantly ($P < 0.01$) in two years. Topping method and row spacing did not affect t_e, the time of reaching maximum W_m. The effects of topping and row spacing treatments on the maximum daily growth rate (C_m) were significantly different ($P < 0.05$) (Table 2; Fig. 4). Chemical topping delayed the time of reaching maximum daily growth rate (t_m) by 1.4 days on average.

3.3. Sap velocity and stem water potential

The sap velocity in chemical topping (on average 15.6 cm hr^{-1}) was higher than in manual topping (13.5 cm hr^{-1}), especially in 2020. The mean sap velocity in equal row spacing was 14.3 cm hr^{-1}, while that in narrow-wide rows was 15.2 cm hr^{-1} (Fig. 5). Sap velocity was generally close to zero at night, but sometimes was much higher than zero, for example in the periods from 77 to 80 DAS in 2020, which was probably caused by a high night air temperature (above 20 °C) (Fig. 5a and b).

Stem water potential in cotton showed an opposite trend with sap velocity that was close to zero at the nighttime and reached a peak value of − 2 to − 2.5 MPa at noontime. Dislike sap flow, the water potential did not have a plate during daytime (Fig. 6).

3.4. Daily and total transpirations

The daily transpiration per unit ground area (DTr) differed

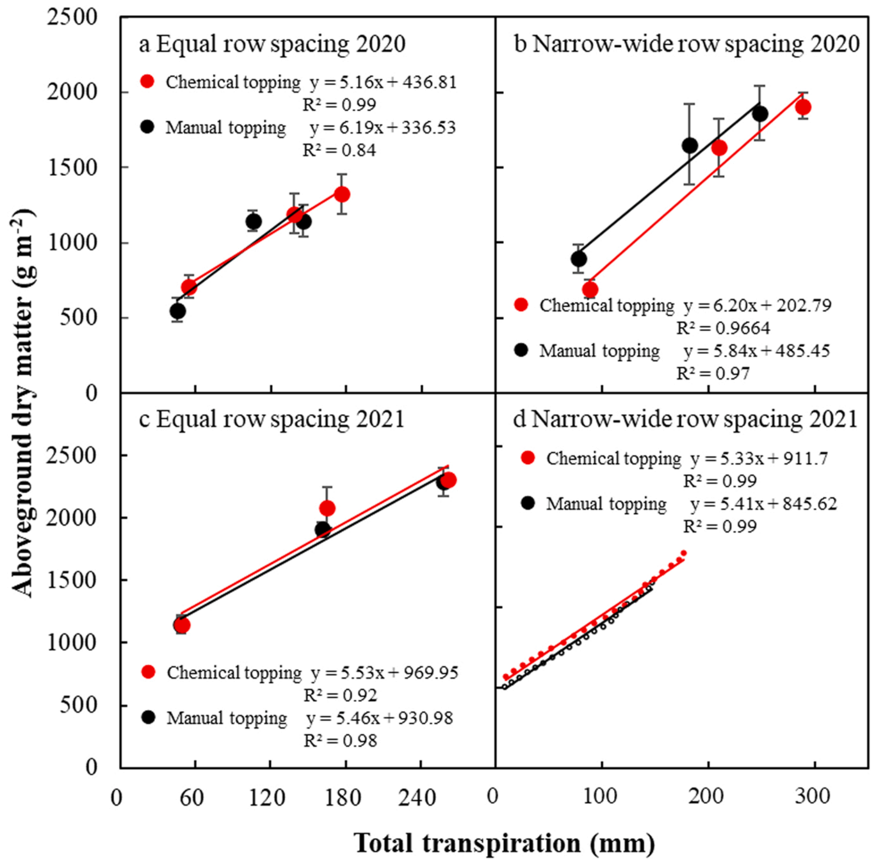

Fig. 10. Linear regressions between aboveground dry matter and total transpiration during cotton flowering to boll open period in Shihezi, China in 2020–2021. The data for narrow-wide spacing in 2021 (d) is fitted aboveground dry matter because of insufficient observed data during the period.

significantly between topping treatments except for the equal row spacing in 2021 (Fig. 7). The *DTr* in chemical topping on average was 4.69 mm d^{-1} during flowing to boll open period in 2020 and 6.45 mm d^{-1} in 2021, while the *DTr* in manual topping was 3.78 mm d^{-1} in 2020 and 5.93 mm d^{-1} in 2021. The mean daily transpiration in equal row spacing across two years was 4.35 mm d^{-1}, significantly lower than in narrow-wide rows (6.42 mm d^{-1}). The *DTr* in all treatments showed a high seasonal variation ranging from 2 to 12 mm d^{-1} (Fig. 7), likely because of the variation of climate factors. The total transpiration during flowering to boll open period was higher in chemical topping than in manual topping in both row configurations and years, especially in 2020 (Fig. 8).

3.5. Water use efficiency

At a daily base, water use efficiency for aboveground dry matter varied largely during cotton reproductive period, and reached the maximum value of 8.13 kg m^{-3} in 27 July 2020 and 11.4 kg m^{-3} in 31 July 2021 (Fig. 9). Chemical topping had no significant effect on daily WUE except for that in narrow-wide rows in 2020. Daily WUE of cotton differed significantly between years, on average 5.70 kg m^{-3} in 2021 and 4.80 kg m^{-3} in 2020.

The linear regression between aboveground dry matter and total transpiration during flowering to boll open period showed strong linear relationships for all treatments and years with R^2 above 0.84. The overall WUE, the slope of the regression lines, was 5.64 kg m^{-3} across all years and treatments (Fig. 10) and showed no difference.

4. Discussion

Compared with manual topping, chemical topping increased leaf area index by 13%, but did not affect cotton yield. The cotton yield also showed no difference between two row spacing treatments. The sap velocity of drip-irrigated cotton ranged from 20 to 45 cm hr^{-1} at the daytime and 0–10 cm hr^{-1} at the nighttime. The daily transpiration in chemical topping was 14.8% higher than in manual topping. The WUE during cotton flowering to boll open period showed no significant difference between all treatments and years in well-irrigated cotton, thus our hypothesis was denied; however, daily WUE showed a high seasonal variation.

Chemical topping did not affect WUE in cotton because it enhanced both biomass and plant transpiration proportionately due to the increase in LAI. However, the WUE in chemical topping was higher than in manual topping in narrow-wide row spacing in 2020 (Fig. 9b). In narrow-wide row spacing, the chemical topping might lead to a more compact architecture than manual topping because of denser canopy (Tung et al., 2019) than in equal row spacing. That allows more light penetrating to the lower canopy, and increases photosynthetic area (Mao et al., 2014), and results in a better light capture and use efficiency. The water potential during the daytime was above − 2.5 MPa and well recovered to zero during the night (Fig. 6), which showed plants were in a good water supply (Cochard et al., 1992). This confirms that cotton in the experiments, especially in 2021 suffers no water stress. In the absence of water stress, the WUE of crops is mainly determined by LAI and biomass growth (Kato et al., 2004). The high dry matter is mainly caused by high transpiration (Kobata et al., 1996), making a consistent WUE of a crop. For high variation of daily WUE, the peak values occurred in July because of the decrease in plant transpiration, probably due to sharp decreases in air temperatures and radiation, however, it might not affect cotton growth quickly because buffer pool would supplied assimilates for crop growth during a short period when daily photosynthesis was insufficient (Zhang et al., 2008b).

Plant growth is affected by plant population and mepiquat chloride.

Compared to manual topping, chemical topping increased plant height, number of fruiting branches and reduced internode length of fruiting branches. That would cause a compact canopy and likely increased light capture, biomass accumulation and the proportion of reproductive organs, thus increased plant transpiration and yield.

The plant transpiration measured by sap flow meter in chemical topping was higher than that in manual topping in two years and two row spacing. The increasing plant transpiration occurs almost simultaneously with leaf expansion (Fernandez et al., 1992), suggesting that plant transpiration in chemical topping is mainly determined by leaf area index. After chemical topping, the cotton plant would grow little bit further, 2–3 more leaves in a short period and lead to a larger LAI than in manual topping. The newly appeared young leaves might have high transpiration (Pantin et al., 2013) because leaves that exposure to light have high transpiration due to favorable ambient temperature and radiation intensity (Fernandez et al., 1992; Colaizzi et al., 2014). Mepiquat chloride increases the stomatal conductance and nitrate reductase activity of plants, and promotes water uptake and root growth by increasing lateral root formation through endogenous hormones (Wu et al., 2019). This is likely another reason for the explanation of high transpiration in chemical topping. Plant transpiration is affected not only by internal factors such as canopy structure and root systems but also by external factors such as climatic and soil conditions. In this study, soil moisture was always abundant due to drip irrigation and plastic film cover, therefore the factors that affecting plant transpiration could mainly be climate factors, e.g., air temperature, humidity, radiation and weed speed. The relationship between plant daily transpiration and climate factors requires a further study.

The sap flow measured by HRM showed a similar course with the evapotranspiration that estimated using Penman-Monteith method, and was closely related to air temperature and photosynthetic active radiation (Wei et al., 2020). Our result for plant transpiration (4.3–6.5 mm d^{-1}) was close to previous estimation of potential evapotranspiration (ET_C) in cotton during reproductive growth period (5.9 mm d^{-1}) based on Bowen ratio and Penman-Monteith methods (Bezerra et al., 2010), but higher than ET_C based on remote sensing and SEBAL algorithms (3.5 mm d^{-1}) (Jose et al., 2020). To our knowledge, our study is the first time to directly quantify sap flow and plant transpiration in cotton with high accuracy. However, due to the limitation of instruments, we only measured one plant per treatment, it existed certain limitations. The HRM only measures sap flow of a single plant, and likely causes an error when calculating to plant transpiration per unit ground area if the stem diameter and plant population density are not well identified (Zhang et al., 2014). To minimize the limitations in sap flow measurements, we measured three plants per plot for stem diameter and aboveground dry matter for calculating the transpiration per plant and per unit ground area, and did same measurements in two years to draw reliable conclusions.

5. Conclusions

The heat ratio method was used to determine sap flow, transpiration and water use efficiency with high accuracy in cotton. Chemical topping increased cotton growth and transpiration comparing with manual topping. Under drip-irrigation and film cover, cotton growing in machine-harvesting row spacing showed same water use efficiency in all testing topping and row spacing treatments. Our results demonstrate that direct measurement of sap flow is a powerful tool to optimize irrigation managements. The quantitatively determining transpiration at field conditions is valuable for understanding plant-water relations and improving crop models.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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